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The Glass Produced from Recycled Soda-Lime Glass Cullet by Slip Casting Technique

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Abstract
Slip casting is a ceramic processing technique that can be utilized for creating ceramic objects with complex shapes. In this study, slip casting was employed to fabricate green samples measuring 70 mm × 10 mm × 15 mm from recycled soda-lime glass. A slip with 60% solid loading was prepared from 100 g of recycled cullet, 1 g of sodium silicate as a binder, 50 ml of DI water, and 16.7 ml of deflocculant. A 0.1 wt% sodium tripolyphosphate solution was used as the deflocculant for slip casting. After the slip casting process, the samples were dried at room temperature for 3 days. Subsequently, they were sintered at 680, 700, and 720 °C for 1 and 2 hours with a heating rate of 5°C/min. Statistical analysis of the results revealed a high degree of variation in the flexural strength, which is attributed to the high closed porosity and pore-size variation of the samples. Therefore, the glass produced from slip casting is not suitable for load-bearing applications. Nevertheless, this technique can still be utilized to create other art products, such as Buddha amulets.

Keywords: Glass, Cullet, Recycle, Slip casting, Four-points bending test, Weibull modulus

1. Introduction

The glass industry in Thailand is substantial, with an annual production capacity of 3 million tons for glass-bottle manufacturing and 1 million ton for flat-glass manufacturing. The production process generally involves mixing raw materials such as silica sand (SiO_2), limestone ($CaCO_3$), and soda ash (Na_2CO_3), which are then melted at approximately 1500 °C and formed into products such as glass bottles or flat glass. Natural gas is a common source of heating in the glass industry and contributes to 75% to 85% of the total greenhouse gas emissions. Additionally, 15% to 25% of greenhouse gas emissions result from the chemical reactions of raw materials.

Cullet is recycled glass, and its properties remain unchanged even after several recycling cycles. When cullet is melted, there are zero greenhouse gas emissions, making it an environmentally friendly alternative to virgin materials. Thus, substituting virgin materials with cullet is an effective method to reduce greenhouse gas emissions and the consumption of non-renewable natural resources in the glass industry. Furthermore, reducing the operating temperature is another approach to further reduce greenhouse gas emissions (Deeprasertwong et al., 2022; Editors, 2021).

Slip casting is a forming method used to create ceramic products. A slurry, consisting of ceramic powder, deflocculant, and water, is prepared and poured into a plaster of Paris mold. The water from the slip is absorbed by the mold, resulting in the formation of a solid layer on the mold's walls. Once the solid layer reaches the desired thickness, excess slip is poured out, leaving behind the green product. Slip casting is particularly useful for producing complex-shaped ceramic products, including pottery and sculptures (Askeland, Fulay, & Wright, 2010; Callister Jr, & Rethwisch, 2014; Tempelman, Shercliff, & van Eyben, 2014). Slip casting has been utilized by various research groups as a sample fabrication method for glass composite systems, including the cordierite/glass powder system (Marghussian & Geramian, 1999; Mei, Yang, & Ferreira, 2003), and hydroxyapatite/ borosilicate glass powder system (Hu & Miao, 2004).

Soda-lime glass is a commonly used commercial glass to produce glass bottles and flat glass. In Thailand, approximately 924,019.55 tons of glass bottles and 722,944.01 tons of flat glass were produced in 2017. Unfortunately, after their use, these glass products are often disposed of in landfills, contributing to environmental issues.

In the previous research, we investigated the use of soda-lime glass cullet recycling through the powder pressing method to form samples. The findings revealed that the samples sintered at 700°C, with a heating rate of 5°C/min and soaking time of 1 hour, exhibited the best properties. Additionally, due to the lower temperature used in the process, there was a significant reduction in greenhouse gas emissions compared to conventional glass manufacturing methods (Deeprasertwong et al., 2022).

The objective of this study was to assess the feasibility of utilizing the slip casting technique for the recycling of soda-lime glass cullet. The mechanical and physical properties of the sintered samples, including flexural strength, shrinkage, and porosity, were examined, and correlated with the observed microstructure. The results were subjected to a statistical analysis to evaluate the viability of this technique for glass recycling.

2. Materials and Methods

The ground cullet used in this study was prepared from waste soda-lime glass, which was crushed using ball milling for a duration of 16 hours. The waste soda-lime glass was obtained from Glassbridge Co., Ltd. The average particle size of the ground cullet was determined to be 891±22 μm using a laser particle size analyzer (Malvern mastersizer 3000). The particle size distribution of the ground cullet is illustrated in Figure 1. The chemical composition of the ground cullet was analyzed using an x-ray fluorescence spectrometer (XRF, Bruker s8 tiger), and the results are presented in Table 1.

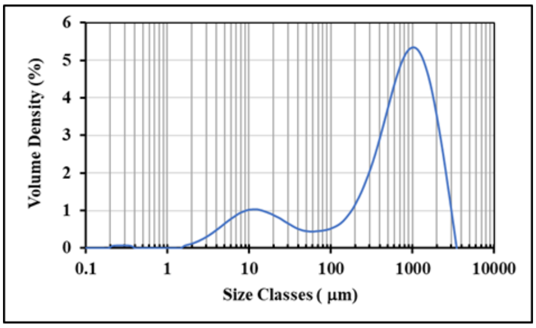


Figure 1. the particle size distribution of the ground cullet.

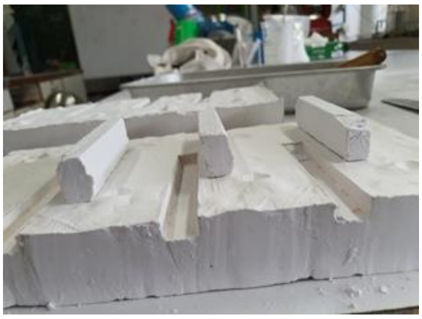
Table 1. the chemical composition of the ground cullet.

Oxide	wt%	Oxide	wt%
SiO_2	69.9	MgO	4.17
Na_2O	14.1	Al_2O_3	1.50
CaO	8.78	Others	1.55

To prepare the slip, a mixture of 100 g of ground cullet, 1 g of binder (sodium silicate), 50 ml of water, and 16.7 ml of deflocculant was used. The slip had a solid loading of 60%. The deflocculant utilized was a 0.1 wt% sodium tripolyphosphate solution, provided by Source Runner Enterprise Co., Ltd.

The slip was carefully poured into plaster molds to create green samples with dimensions of 70 mm × 10 mm × 15 mm. Figure 2 (a) depicts the plaster molds filled with the slip. Once the casting process was completed, the green samples were extracted from the molds, as shown in Figure 2 (b) and left to air dry for a period of 3 days. Subsequently, the dried samples were subjected to sintering, as depicted in Figure 2 (c). The sintering process involved temperatures of 680°C, 700°C, and 720°C, with soaking times of 1 and 2 hours, and a heating rate of 5°C/min.

(a)



(b)

(c)

Figure 2. the different stages of the sample preparation process: (a) the plaster molds filled with the slip, (b) the green samples just after being removed from the molds, and (c) the green samples prior to undergoing the sintering process.

The flexural strength of the sintered samples was evaluated using a four-point bending test performed on a universal testing machine (UTM, Instron 5969). Additionally, the microstructure of the sintered samples was analyzed using a scanning electron microscope (SEM, Hitachi SU3500). To determine the closed porosity of the sintered samples, the Archimedes method was employed, and the calculation was carried out using the following equation:

$$CP = TP - AP \qquad (1)$$

where CP, TP, and AP refer to the closed, true, and apparent porosity of the samples, respectively. As AP represents interconnected pores, and TP represents both interconnected pores and closed pores, the CP of a sample can be calculated using Equation (1).

TP and AP can be calculated using Equations (2) and (3) as follows:

$$TP = [(\rho - BD)/\rho] \times 100 \qquad (2)$$

$$AP = [(W_2 - W_1)/(W_2 - W_3)] \times 100 \qquad (3)$$

ρ represents the true density of soda-lime glass, which is approximately 2.47 g/cm³ (Ashby, 2013; Deeprasertwong et al., 2022), while BD, as obtained from Equation (4), represents the bulk density.

$$BD = W_1/(W_2 - W_3) \qquad (4)$$

where W_1 represents the dry weight of the sample, W_2 represents the weight of the sample just after being removed from the water, and W_3 represents the weight of the sample measured in water (Askeland et al., 2010).

For each test on mechanical and physical properties, three samples from each experimental condition were used.

Statistical analysis was conducted on the flexural strength data. The probability of sample failure (F), due to the applied stress (σ) is (Askeland et al., 2010)

$$F = 1 - e^{(-[\sigma/\sigma_o]^{m_o})} \text{ or} \qquad (5)$$

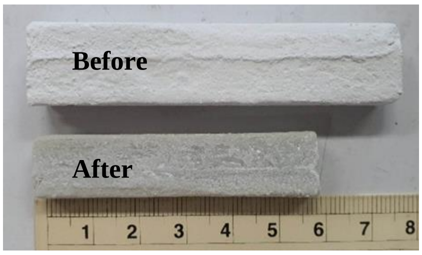
$$ln\left\{ln\left[\frac{1}{1-F}\right]\right\} = m_o(ln(\sigma) - ln(\sigma_o)) \qquad (6)$$

In the equation, σ_o represents a parameter that depends on the size and shape of the sample, and m_o denotes the Weibull modulus.

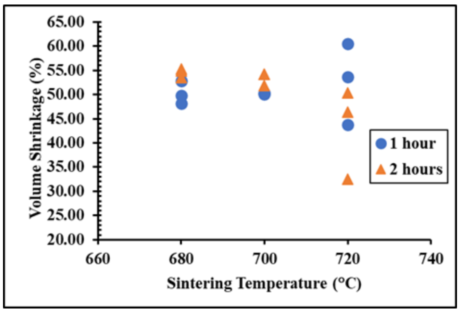
According to Askeland et al. (2010); the Weibull modulus of a set of flexural strength data can be determined by ranking the data from lowest to highest. For a set of n samples, each sample is assigned a numerical rank from i = 1 to n, with i = 1 representing the sample with the lowest flexural strength. F is then assigned to each sample, and for sample i, F can be calculated as i / (n + 1). Afterward, a graph is created with the y-axis representing ln{ln(1/(1-F))} and the x-axis representing ln(σ). The Weibull modulus can be determined by applying linear regression analysis to the graph. In the context of a load-bearing ceramic part, a large value of the Weibull modulus is desirable as it indicates a narrow range of flaw sizes within the material.

3. Results and Discussion

Figure 3(a) depicts the samples before and after the sintering process, revealing a significant shrinkage following sintering. The volume shrinkage of each sintered sample is presented in Figure 3(b). Notably, the volume shrinkage remains relatively consistent across both soaking times (1 and 2 hours) and all sintering temperatures (680, 700, and 720 °C). Figure 4 illustrates that the sintered samples possess a porous structure with varying pore sizes. The closed porosity of each sample is displayed in Figure 5, demonstrating a similar trend to the volume shrinkage, with consistent closed porosity observed across both soaking times and all sintering temperatures.

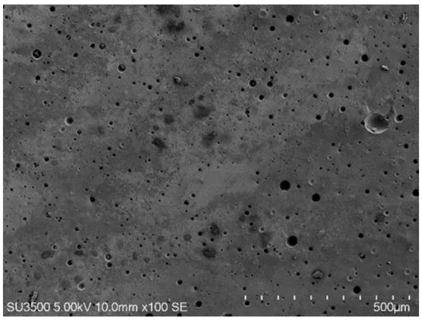


(a)

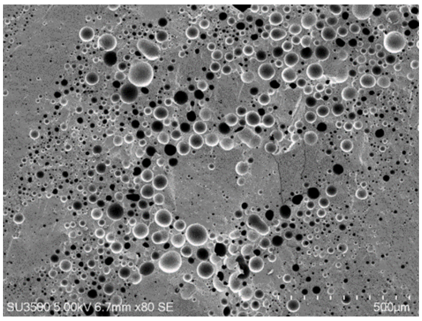


(b)

Figure 3. (a) a comparison of the sample size before and after sintering (b) the volume shrinkage that takes place after sintering.



(a)



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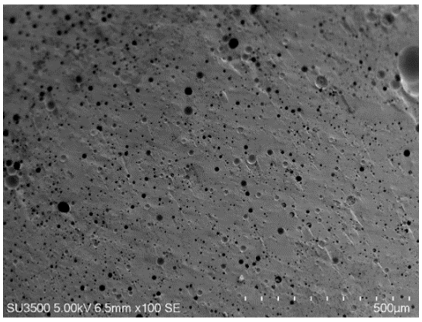

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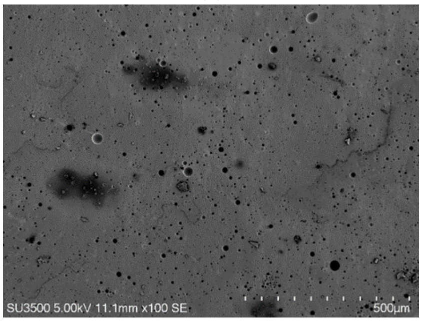

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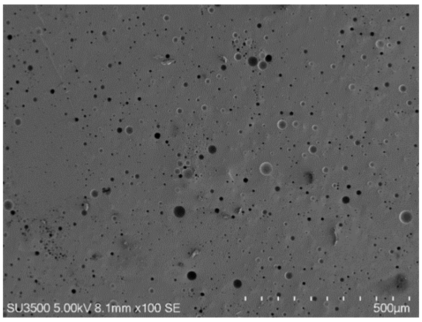

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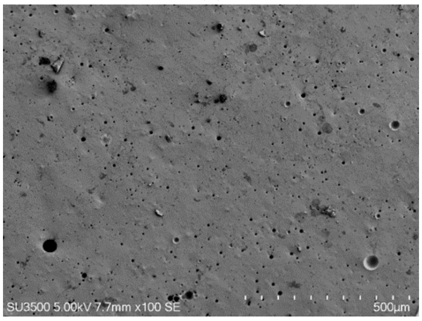

(f)

Figure 4. the microstructure of the samples after sintering at different temperatures and holding times. The images show the microstructures for the following conditions: (a) 680°C and 1 hr (b) 680°C and 2 hrs (c) 700°C and 1 hr (d) 700°C and 2 hrs (e) 720°C and 1 hr (f) 720°C and 2 hrs.

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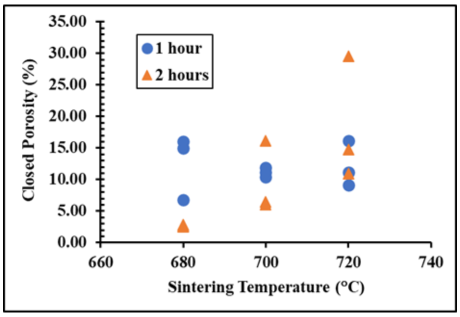
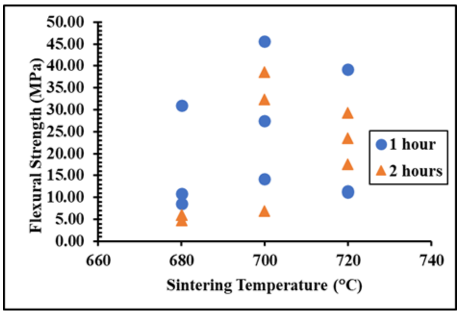


Figure 5. the closed porosity of the sintered samples.

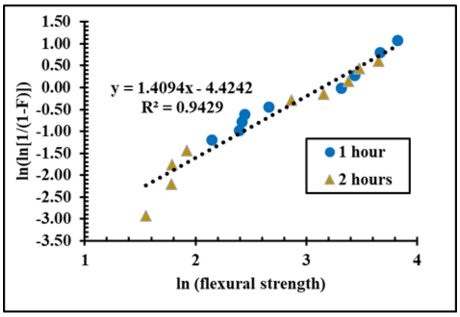
According to Askeland et al. (2010), defects can be generated inside ceramics and glasses during the manufacturing process. Additionally, microcracking on the glass surface may occur due to the interaction between glass and water vapor in the air. The size and distribution of internal defects have a significant impact on the strength of ceramics and glasses.

Figure 6(a) illustrates the flexural strength of each sample. The data from both soaking times and various sintering temperatures were used to generate the straight line for Weibull statistical analysis, as shown in Figure 6(b). The Weibull modulus (m_o from Equation (6)) represents the slope of the straight line in Figure 6(b), which is calculated to be 1.409. Conventionally-prepared alumina typically exhibits a Weibull modulus around 4.7, while advanced ceramics can have Weibull moduli ranging from 10 to 20 (Askeland et al., 2010). Therefore, the Weibull modulus obtained in this work is considerably low. This low Weibull modulus suggests a high variation in flexural strength, which is likely due to the presence of high closed porosity and variations in pore size resulting from the sintering process (Figures 4 and 5).

Considering the low Weibull modulus observed in glass samples produced from recycled soda-lime glass cullet through slip casting, it is evident that these materials are not suitable for load-bearing applications. However, it should be noted that slip casting is widely employed in the creation of various art products. In this study, we utilized slip casting to produce art pieces such as the Buddha amulets depicted in Figure 7. These amulets demonstrate the capability of the glass slip casting technique for recycling glass and crafting intricate and aesthetically pleasing glass objects with artistic value.



(a)



(b)

Figure 6. (a) flexural strength of the sintered samples and (b) Weibull statistical analysis on flexural strength data.

(a)

(b)

Figure 7. (a) Buddha amulets before and after sintering (b) various Buddha amulets.

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4. Conclusions

Slip casting was investigated as a method for recycling soda-lime glass. The process involved crushing the waste soda-lime glass using ball milling, sieving it, and then mixing it with a binder, deflocculant, and water to prepare the slip for slip casting. The green samples obtained after casting were subsequently sintered. Statistical analysis of the flexural strength data of the sintered samples revealed a significant variation in strength, indicating that the glasses produced through slip casting were not suitable for load-bearing applications. As a result, the glass slip casting process was employed to create art products, such as Buddha amulets.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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